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Influence of low energy Ar-sputtering on the electronic properties of InAs-based quantum well structures

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The influence of low energy (80–500 eV) Ar-ion milling cleaning techniques on InAs based quantum well structures is investigated. It is found that both etching with a Kaufmann source and sputter-etching with a rf-plasma enhances the electron density and reduces the mobility. An anneal at 180 °C has little effect, and only recovers damage caused by low energy (80 eV) Kaufmann etching. © *1995 American Institute of Physics.*

InAs based quantum well (QW) structures are increasingly being used to study electronic transport in the ballistic regime.[1,2] Due to the pinning of the Fermi level, at the InAs surface, in the conduction band the metal-InAs contacts lacks a Schottky barrier. Because of this, it is not necessary to alloy the contact, which needs to be done to make contact to the 2DEG in a GaAs/AlGaAs heterostructure, and therefore the contact is free of a diffusive contact area usually present in alloyed contacts. This is especially important when the electron transport should remain ballistic up to the metal contact, for instance in superconductor-2DEG-superconductor junctions,[3,4] or in the case of magnetic contacts, to investigate spin-polarized transport.[5,6]

A standard procedure in making metal contacts to a semiconductor, for instance InAs, is an *in situ* cleaning of the InAs surface by low energy, 100–500 eV, Ar-ion milling prior to metal deposition, to remove the natural oxide present at semiconductor surfaces. Millea *et al.*[7,8] studied the effect of low energy Ar bombardment on the surface conductivity of *p*-InAs. They showed that low energy Ar bombardment enhances the electron density in the 2DEG present in the inversion layer at the surface of *p*-InAs. The increase of the electron density can have two causes, either the Fermi-level pinning at the surface is changed, or, as assumed by Millea *et al.* donor states are introduced. We will show that the latter is more likely. The introduction of donor states upon low energy Ar bombardment is a result of the unique radiation damage properties of InAs.[9] Radiation (high energy electrons, low energy ions) introduces point defects, that consist of shallow donors, near the surface. Millea *et al.*[8] interpreted their results by assuming these point defects can migrate into the bulk, up to a depth of 0.1 μm. Because in the bulk samples used by Millea *et al.* the introduced donors are far below the surface, and thus spatially separated from the 2DEG, the mobility μ_e increases with increasing sheet electron density n_s as a result of enhanced screening of scatterers.

So far, however, no systematic study has been made to investigate the influence of the Ar-ion milling on the electronic transport properties of the 2DEG present in an InAs QW. In this letter we compare the influence on the 2DEG in an InAs QW of two commonly used cleaning techniques, Kaufmann sputtering with low energy Ar atoms, and rf sputter-etching with an Ar plasma. We find an increase of the electron density in the QW with the applied Ar dose, as did Millea *et al.* For the mobility we find that it decreases drastically with the Ar dose, opposed to the result found by Millea *et al.* for the 2DEG present in the inversion layer of *p*-InAs.

In a Kaufmann source, Ar atoms are ionized, and accelerated by means of a high voltage between cathode and acceleration grid. The flux of Ar atoms is determined by measuring the ion-beam current on a shutter, with a well-defined area, prior to neutralizing the beam. In rf-sputter etching, a plasma of Ar ions and electrons is created using a high voltage and a rf signal. A self-bias will occur in the plasma, which directs the Ar ions toward the sample. In general the etch rate using a Kaufmann source is much higher than for rf-sputter etching with the same Ar flux. This is because the working pressure used in rf-sputtering is much higher, resulting in scattering between ions, which reduces their forward energy toward the substrate.

For cleaning purposes it is only needed to etch 10–20 Å, the typical thickness of the natural oxide on semiconductors. Etching more would unnecessarily roughen the surface. Furthermore, if the thickness of a QW is reduced, the quantized energy levels will shift up in energy, and as a result the electron density will go down. Samples consist of a standard Hall bar geometry in a GaSb/AlSb/InAs/AlSb heterostructure, with a 2DEG present in the 15 nm thick InAs layer. The GaSb/AlSb top layer is removed chemically, exposing the InAs layer, just before the samples are Ar etched. We used two different wafers, G1425 and G1481, with comparable layer structure, but different transport parameters; see Table I. To cover a wide variety of Ar energies, from low to moderate, we investigated four different etching procedures; Kaufmann etching, (i) 500 eV, with a measured etch rate per

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TABLE I. Electronic transport properties obtained from longitudinal- and Hall-resistance measurements.

Sample	Energy (ev)	Dose (mC/cm^2)	n_s (10^{16} m^{-2})	μ_e (m^2/V s)	Etched (Å)
Wafer G1425					
Bare sample, top-layer removed					
	⋯	⋯	1.1	2.2	
Kaufmann sputtering					
A	500	1.06	20	0.02	20.0
B	100	1.05	5.4	0.4	
C[a]	100	1.08	4.3	0.5	
Wafer G1481					
Bare sample, top-layer removed					
H2	⋯	⋯	0.59	0.69	
H7	⋯	⋯	0.54	0.87	
H7[b]	⋯	⋯	1.07	1.00	
H11	⋯	⋯	0.56	1.23	
H11[c]	⋯	⋯	1.14	1.03	
Kaufmann sputtering					
H3	80	0.53	0.89	2.2	
H3[b]	⋯	⋯	1.3	1.2	
H4	80	1.06	1.1	1.9	
H4[b]	⋯	⋯	1.3	1.3	
H6	80	2.11	1.6	0.8	
H6[b]	⋯	⋯	1.2	1.3	
H8	170	2.5	8.2	0.14	11.3
H8[b]	⋯	⋯	7.5	0.14	
H9	170	5.1	8.5	0.14	23.0
H10	155	6.7	8.4	0.17	30.1
rf sputtering					
H12	400	4.6	2.36	0.72	9.2
H12[c]	⋯	⋯	11.4	0.076	
H13	400	9.1	11.9	0.084	18.2
H13[c]	⋯	⋯	11.4	0.082	
H14	400	13.7	14.7	0.069	27.4
H15	400	18.3	15.6	0.072	36.6

[a]Sample C was etched using Xe instead of Ar.
[b]After 20 min anneal at 180 °C.
[c]After 10 min anneal at 180 °C.

Ar flux of 19.3±0.9 Å/(mC/cm^2), (ii) 150 eV, etch rate 4.5±1.0 Å/(mC/cm^2), (iii) 80 eV, etch rate negligible (not measurable), and rf plasma sputtering, (iv) 400 eV, etch rate 2.0±0.2 Å/(mC/cm^2). In all measurements a maximum of 37 Å of InAs was etched; see Table I. Measurements are done immediately after the sputter treatment, in order to prevent aging effects. The longitudinal and Hall resistance are measured at 4.2 K, using a standard four point lock-in technique, as a function of magnetic field. From these measurements we extract the carrier density and mobility of the 2DEG in the InAs QW, listed in Table I. Figure 1 shows the dependence of μ_e and n_s on the dose of Ar atoms, for 80 eV Kaufmann etching (a), and for 400 eV rf sputtering (b). As can be seen, at low energy and low dose n_S increases linearly with the Ar dose [Fig. 1(a)]. The efficiency, the number of introduced donors per incoming Ar atom, is very low, 10^{-4}. From Table I we can see that the efficiency increases when the energy is increased. At higher energy n_s saturates for very high Ar dose [Fig. 1(b)]. At low Ar-energy μ_e shows a maximum as function of the Ar dose. At higher energy and

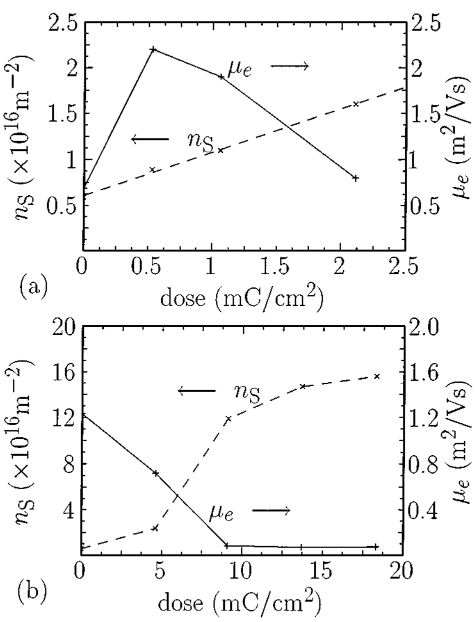

FIG. 1. Dependence of the electron density n_s and mobility μ_e on the Ar dose, for 80 eV Kaufmann etching (a), and for 400 eV rf sputtering (b).

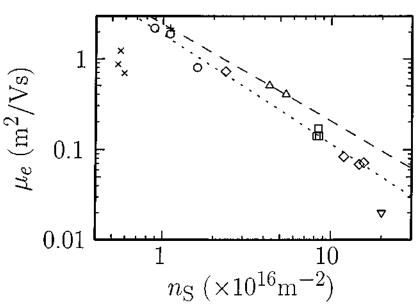

FIG. 2. Mobility μ_e plotted vs the electron density n_s, on a log–log scale. For both wafers a straight line is shown: wafer G1425 (dashed line) slope -1.08 ± 0.01, wafer G1481 (dotted line) slope -1.21 ± 0.04. Individual points: G1425 bare sample (+), 100 eV Kaufmann etched (△), 500 eV Kaufmann etched (▽, ignored in linear fit), G1481 bare sample (×, ignored in linear fit), 80 eV Kaufmann etched (○), 155–170 eV Kaufmann etched (□), and 400 eV rf-plasma sputtered (◇).

dose, μ_e rapidly decreases with Ar dose, saturating at the same dose where n_s starts to saturate.

In a 2DEG we can write for the elastic mean free path l

$$l = v_f \tau = \frac{\hbar k_f}{m^*} \frac{m^* \mu_e}{e} = \frac{\hbar}{e} \sqrt{2\pi n_s}\mu_e . \tag{1}$$

At the same time we can estimate that l will scale with the average distance between the defects, which in a 2D system means

$$l \propto \frac{1}{\sqrt{n_{\mathrm{defects}}}} . \tag{2}$$

Combining Eqs. (1) and (2), under the assumption that all introduced defects act as shallow donors, one finds that μ_e will be inversely proportional to n_s. This is opposite to the dependence found by Millea *et al.*[7] However in an InAs quantum well the radiation-introduced donors will be present in the InAs layer, and therefore not be spatially separated from the 2DEG. In Fig. 2, μ_e is plotted versus n_s on a log–log scale, showing a linear dependence. For wafer G1425 we obtain a slope, by applying a linear fit to the data, of -1.08 ±0.01, and for wafer G1481 we get -1.21 ± 0.04, both reasonably close to the expected slope of -1. The initial rise of the mobility cannot be explained within this model. It can be understood qualitatively by realizing that defects are introduced first at the surface and later also in the InAs layer. Due to the increased electron density n_s the conduction band in the InAs QW will bend in such a way that electrons on average will move away from the surface, and thus suffer less scattering from the surface defects, hence the initial increase of the mobility μ_e. When the electron density is further increased defects in the InAs layer are also introduced, and the mobility will decrease. The sample that has been processed using 500 eV, Kaufmann etching does not fit onto the straight line shown in Fig. 2. In Eqs. (1) and (2) we assume that the electron gas is still 2-D. From n_s and μ_e, given in Table I, we can calculate $l \approx 15$ nm, which is comparable to the thickness of the InAs layer. Therefore in this sample (A) scattering along the perpendicular direction is no longer negligible, and Eqs. (1) and (2) do not apply.

We also studied the effect of annealing at 180 °C. The samples were, with chip carrier, placed in a photoresist oven for 10–20 min, after which they were immediately measured again. In all samples where the Ar-etch removed some of the InAs, the anneal had very little effect, meaning the mobility remained low and the electron density stayed high. Only for the samples that were exposed to 80 eV of Ar atoms, with a negligible etch rate, the damage was recovered by annealing.

The general trend observed is that the electron density n_s increases and the mobility μ_e decreases as a result of Ar sputtering. The linear dependence of μ_e on n_s^{-1} indicates that this is the result of introducing defects that act as donors. Using Xe instead of Ar does not make a significant difference (compare samples B and C). Annealing at 180 °C does not recover the damage introduced by etching, except for the case of 80 eV Kaufmann etching, where the etch rate is negligible, and probably only some minor surface defects are created. Low energy Kaufmann sputtering introduces only small, recoverable, damage, but it does not remove the surface oxide, and is therefore not useful in making good contacts. When higher energy is used the metal-InAs contact is better for two reasons; first, the oxide is removed, and second, the electron density directly under the metal contact is enhanced. When it is, however, essential that n_s and μ_e remain constant underneath a metal contact on top of an InAs QW, Ar sputtering cannot be used for cleaning purposes.

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